Resource Prospector

Mission Goals and Landing Site Constraints

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SSERVI: Lunar Science for Landed Missions Workshop, 2018

Why RP?

RP was spawned to answer fundamental questions about volatile resources on the moon

The lunar science community, commercial industry, and political leaders are interested in better understanding the nature of lunar volatiles, both as an Exploration opportunity to reduce cost of humans in deep space, and for lunar science

RP follows in the footsteps of a number of lunar missions such as Lunar Prospector, SELENE, LCROSS, LRO, Chandrayaan-1, etc

RP is attempting to address all of the GER's ISRU recommendations:

1. Prospect for the lunar resources
2. Demonstrate volatiles resources processing

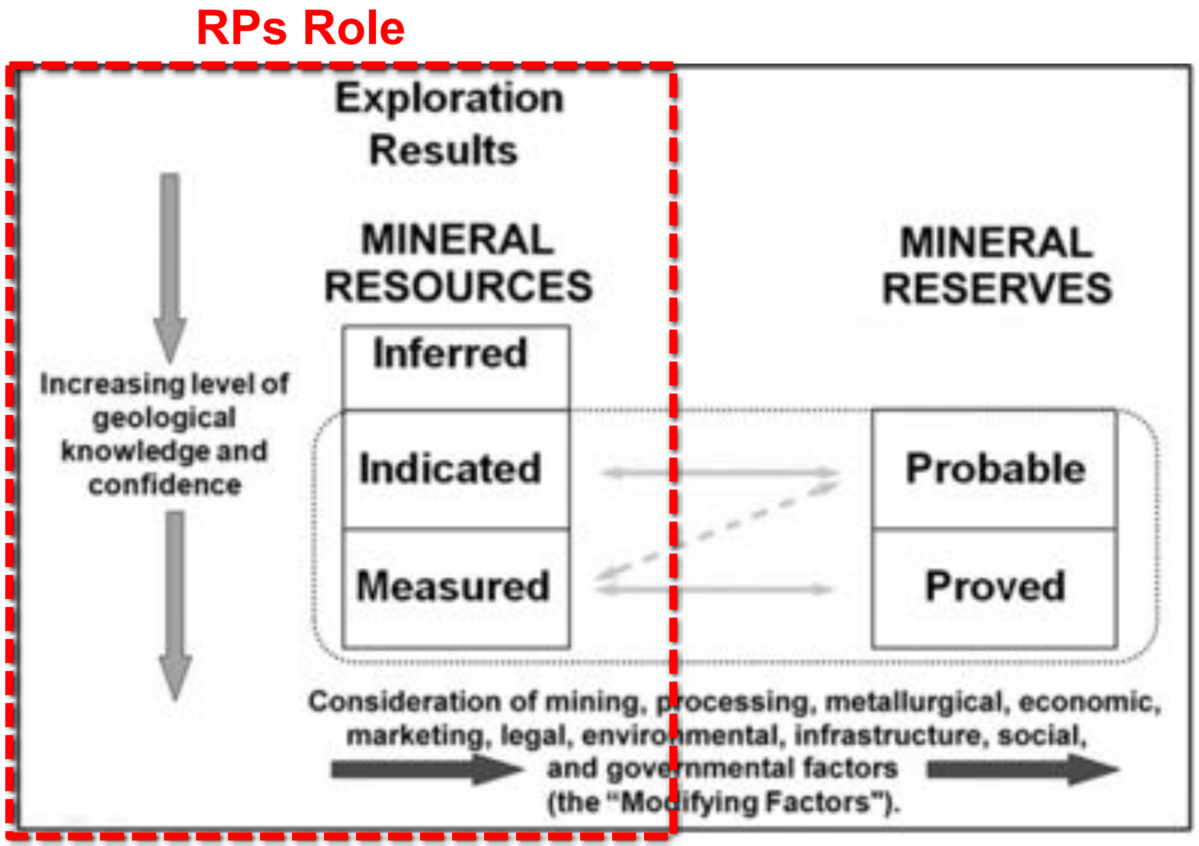
RP: Addressing the Lunar Poles ISRU Potential

Important Parameters for ISRU Viability / Economics

- Volatile distribution (concentration, including lateral and vertical extent and variability)
- Volatile Form (H2, OH, H2O, CO2, Ice vs bound, etc).
- Overburden: How much and type of material needing to be removed to get to ore?
- Working Environment: Sun/Shadow fraction, soil mechanics, trafficability, temperatures

Resource extraction must be 'Economical'

- Need data concerning distribution and accessibility to help determine if a resource and processing technique allows for positive Return on Investment (ROI), including Mass, Cost, Time, and Mission/Crew Safety
- Amount of product needed justifies investment in extraction and processing



From "Committee for Mineral Reserves and International Reporting Standards, 2013

The First Step: Exploration and Prospecting

First Step in Mining is Exploration / Prospecting

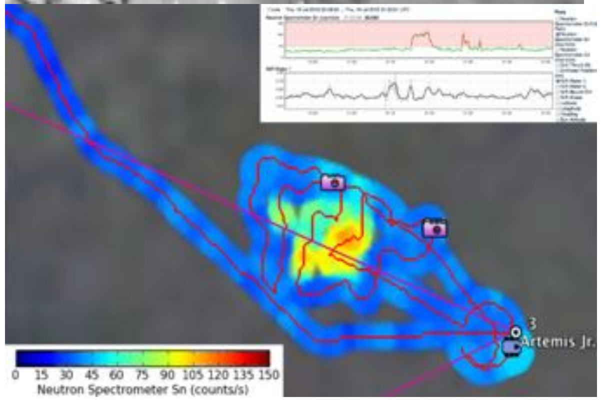
- Need to provide strategic knowledge input to the resource potential / economics: In what locations/environment is the ISRU potential (the Resource Reserves) maximum?

Exploration and prospecting characterizes the location and the extent of the ore that is being sought

- Provide data for studies to the feasibility and economics to access the ore (ore = any material with potential economic or other value)

- Provides the ground truth and linkage between on-site conditions to regional remote sensing data sets

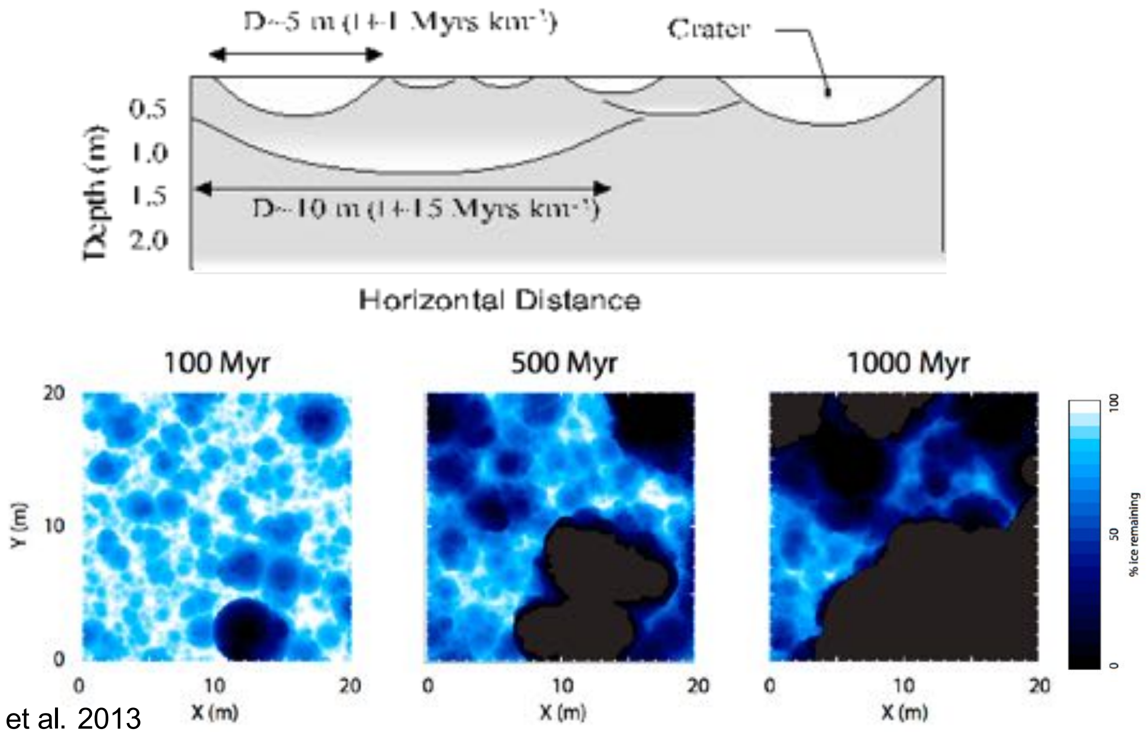
- Tests theories of emplacement and retention that will improve models to predict ore location and grade (concentration)



Resource Spatial Extent and Distribution – Cratering and Temperature

Crater Mixing

- Dominant geological process affecting top meter of regolith is small impact cratering
- Distance between 10m wide craters (~1m deep) is ~50-150m
- Consequently top 0.5 meters is likely to be patchy at scales of ***10s-100s of meters***



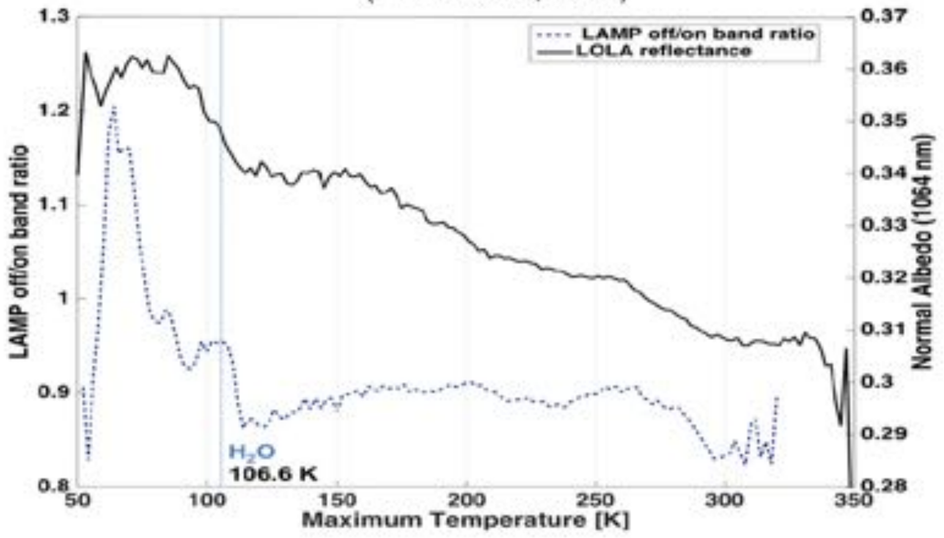
Hurley et al. 2013

Temperature Control

- Temperature appears to be a necessary requirement, but not the only determinant of volatile presence
- Thermal stability is defined as the temperature at which ice is stable in vacuum for geological periods of time (~Gyrs), or around <107K
- ***Temperature variations are largely determined by topography, thus temperature variations will be significant down to scales of <5 meters***

Surface Reflectance vs Temperature Indicative of Surface Frosts

(Fisher et al., 2017)



Understanding the Resource Potential

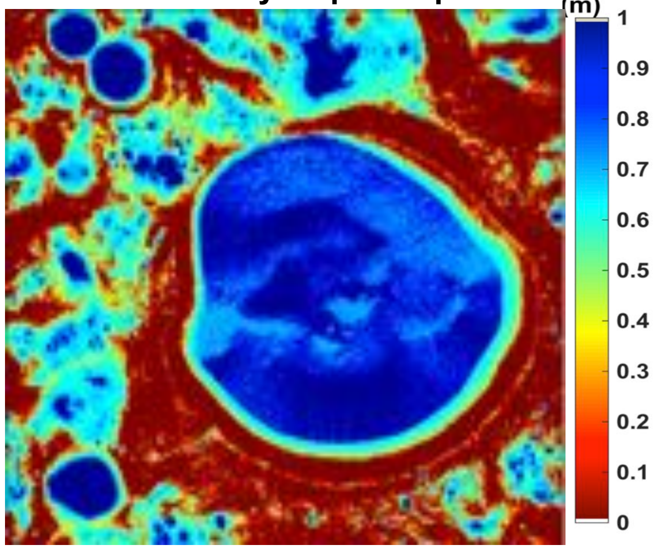
What is the ISRU value of deposits across the range of environments, terrain types and length scales?

Define four environments based on the predicted thermal stability of ice with depth, the **Resource Target Regions** (RTRs):

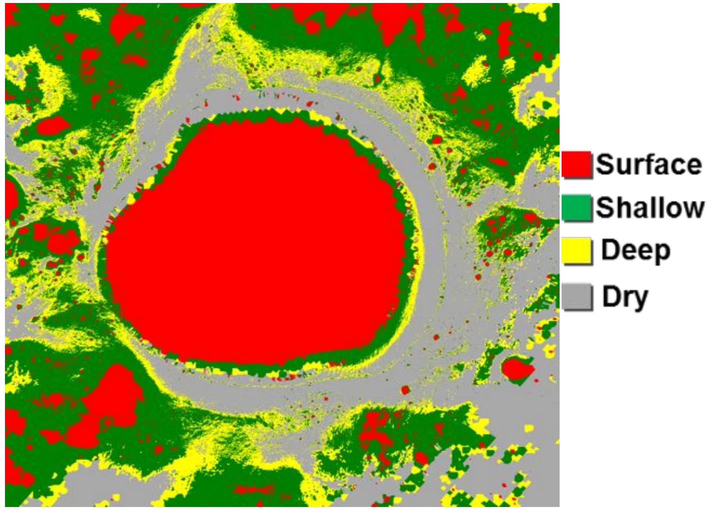
- **Dry**: Temperatures in the top meter expected to be too warm for ice to be stable
- **Deep**: Ice expected to be stable between 50-100 cm of the surface
- **Shallow**: Ice expected to be stable within 50cm of surface
- **Surface**: Ice expected to be stable at the surface (ie., within a Permanently Shadowed Region, PSR)

Is the Resource Need met in a equivalent volume in any of these RTRs? Better (e.g., more economical, safer) in one than another?

Ice Stability Depth Map



Resource Target Region Map



(Siegler and Paige, 2017)

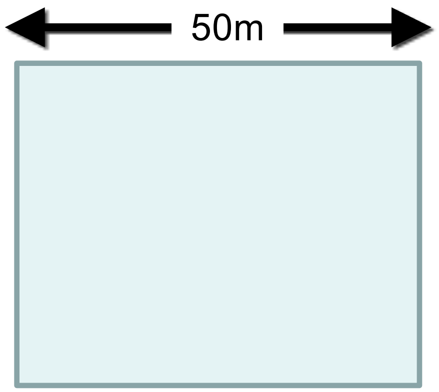
What is the overall productivity of a given Resource Target Regions (RTR)?

A. Need to measure to production fraction for a equivalent volume (Ore Body)
- What is the average water production from a equivalent volume of ore?
- The answer provides scales the production efficiency of a particular thermal region

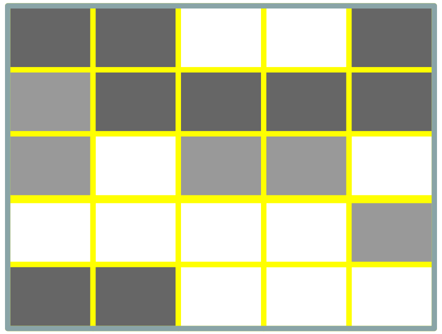
B. Within a equivalent volume what is the variability, or delineation of the ore deposit?
- The answer informs the excavation technique and efficiency: Is the water patchy vs uniform at excavation tool scales?

C. What is the variability from one equivalent volume to the next?
- Answer informs regional production efficiency beyond a single sample site

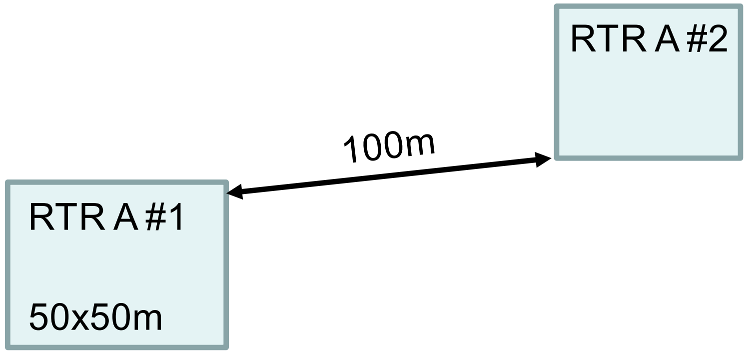
A. Measure total yield of an ore body at scales sufficient to meet need



B. Delineation of the ore deposit across production area



C. Ore grade correlation with thermal environment across relevant geologic scales (>100m)



RP Trace to SKGs

Lunar Exploration Strategic Knowledge Gaps		Instrument or Activity	RP Relevance
I. Understand the Lunar Resource Potential			
D-3	Geotechnical characteristics of cold traps	NIRVSS, Drill, Rover	VH-H
D-4	Physiography and accessibility of cold traps	Rover-PSR traverses, Drill, Cameras	VH
D-6	Composition, Form, and Distribution of Polar Volatiles	NSS, NIRVSS, OVEN-LAVA	VH
D-7	Temporal Variability and Movement Dynamics of Surface-Correlated OH and H2O deposits towards PSR retention.	NSS, NIRVSS, OVEN-LAVA	VH
G	Lunar ISRU production efficiency 2	Drill, OVEN, LAVA-WDD	M-L
III. Understand how to work and live on the lunar surface			
A-1	Technology for excavation of lunar resources	Drill, Rover	M
A-2	Technologies for transporting lunar resources	Planning Products, Cameras	M
B-1	Lunar geodetic control	Planning Products, Cameras, Post Processing	H-M
B-2	Lunar topography data	Rover Cameras	M
B-3	Autonomous surface navigation	Traverse Planning, Rover	M-L
B-4	Autonomous Landing and Hazard Avoidance	Lander	M
C-1	Lunar surface trafficability: Modeling & Earth Tests	Planning, Earth Testing	M
C-2	Lunar surface trafficability: In-situ measurements	Rover, Drill	H
D-2	Regolith adhesion to human systems and associated mechanical degradation	Rover, Cameras, Ops	M-L
D-4	Descent / ascent engine blast ejecta velocity, departure angle and entrainment mechanism - in situ measurements	Lander, Rover Cameras, NIRVSS	M
E-1	Lunar dust remediation	Rover, NIRVSS, OVEN	M
E-2	Regolith adhesion to human systems and associated mechanical degradation	Rover, NIRVSS, OVEN, Cameras	M
E-3	Descent/ascent engine blast ejecta velocity, departure angle, and entrainment mechanism: Modeling	Landing Site Planning, Testing	M
E-4	Descent/ascent engine blast ejecta velocity, departure angle, and entrainment mechanism	Lander, Rover, NIRVSS	H
F-2	Energy Storage - Polar missions	Rover	M
F-4	Power Generation - Polar missions	Rover	M

Decadal Survey: *Lunar Polar Volatile Explorer* Science Objectives

Science Objective (priority)	LPVE Payload (priority)	RP Payload	TRL
Determine form and species of volatile compounds at lunar poles (1)	Drill (1), borehole camera (1), sample acquisition and GCMS (1)	Drill (extraction of cuttings); NIRVSS (multi-color imaging; near-IR spectroscopy); WAVE (GCMS)	6, 5/6, 5
Determine vertical distribution and concentration of volatile compounds in lunar polar regolith (1)	Borehole neutron spectrometer (1), ground-penetrating radar (2)	Drill (extraction of cuttings from multiple depths), NIRVSS (multi-color imaging, near-IR spectroscopy), WAVE (GCMS)	6, 5/6, 5
Determine lateral distribution/concentration of volatile compounds in lunar polar regolith (1)	Rover-borne neutron spectrometer (1), ground-penetrating radar (2), surface imaging (2)	NSS (Rover-borne neutron spectrometer), NIRVSS (near-IR spectrometer surface measurements during prospecting)	6, 5/6
Determine the secondary alteration mineralogy of the regolith (2)	X-ray diffraction (2)	NIRVSS (Near-IR spectroscopy and multi-color imagery of regolith)	5/6
Determine composition and variation in lunar exosphere adjacent to the cold traps (2)	Exospheric mass spectrometer (2)	NIRVSS (Monitor surface volatile variation as a function of surface temperature)	5/6

SCEM Report: Science Goals and RP Capabilities

SCEM Science Goal	RP Payload
4a - Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.	Drill cuttings; GCMS analysis of surface and subsurface volatiles provides chemical and isotopic composition; NIR spectra provides mineralogy; Neutron spectroscopy provides lateral and approximate depth distribution; NIR spectra of extracted drill cuttings provides vertical distribution, as does GC/MS analysis of samples from depth
4b - Determine the source(s) for lunar polar volatiles.	GCMS: Chemical and isotopic composition point to sources; NIRVSS: imagery of physical state and NIR spectra inform emplacement mechanism.
4c - Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions	Drilling/sampling within PSRs: GCMS chemical and isotopic composition reveal likely sources; NIRVSS imagery of physical state and spectra inform emplacement mechanism.
4d - Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith.	Rover slip vs slope, drill penetration force and augering torque with depth, and imaged rover wheel/surface interaction provide geotechnical info
4e - Determine what the cold polar regolith reveals about the ancient solar environment.	Not directly addressed.

Landing Site Requirements

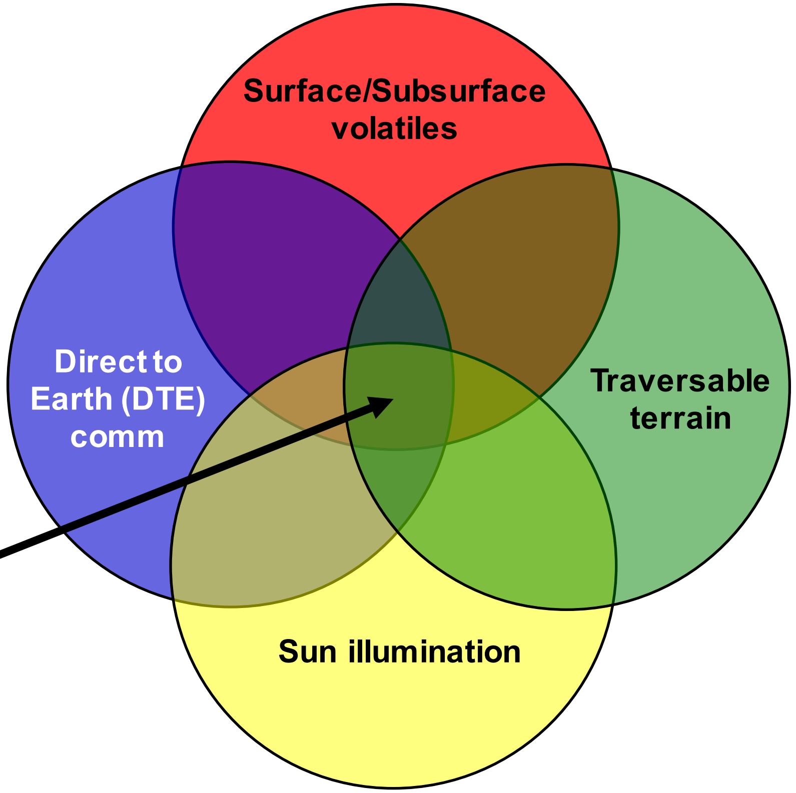
Landing site requirements are driven by L1.1:

1.1 RESOURCE PROSPECTOR SHALL LAND AT A LUNAR POLAR REGION TO ENABLE PROSPECTING FOR VOLATILES

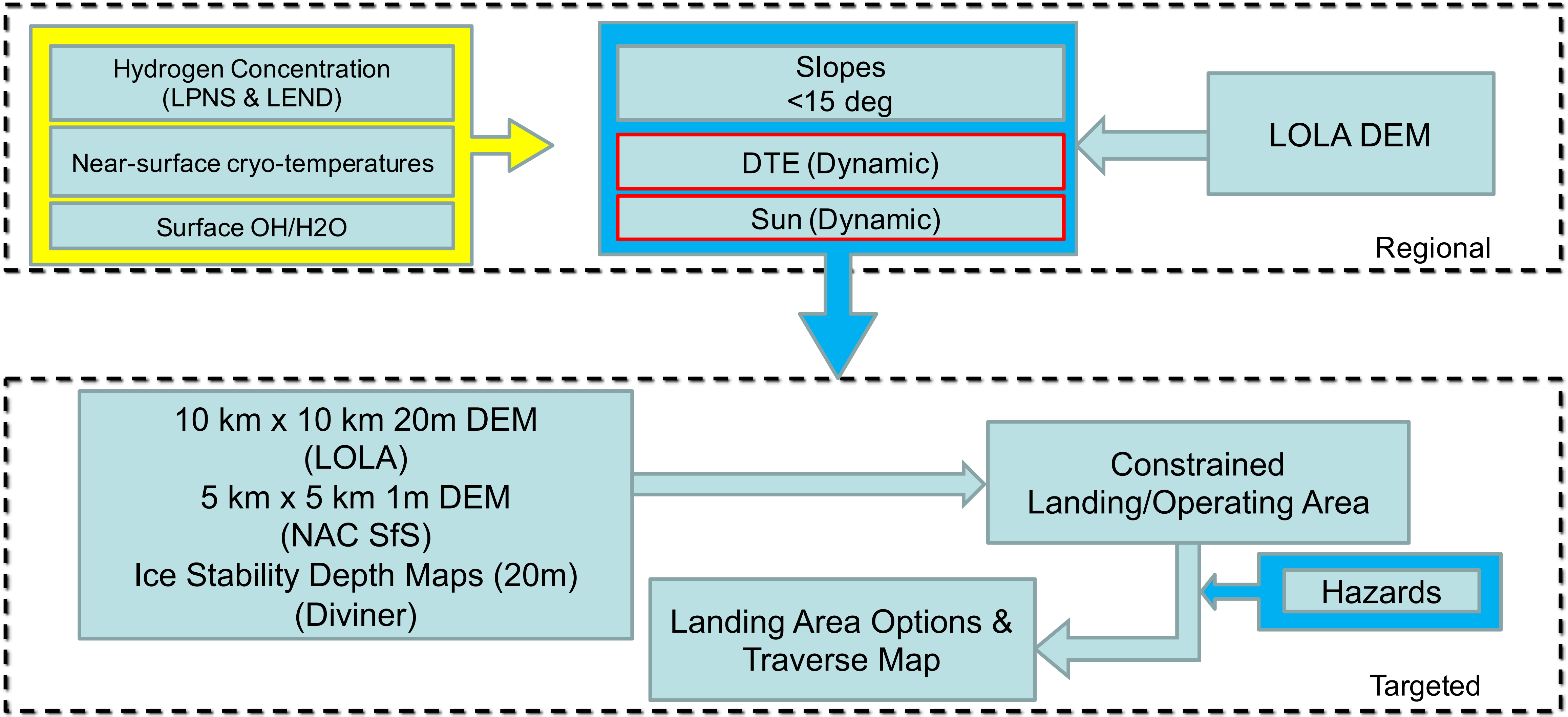
Full Success Criteria: Land at a **polar location** that maximizes the combined potential for obtaining a **high volatile (hydrogen)** concentration signature and **mission duration** within **traverse capabilities**

Good candidate polar landing sites meet these four criteria:

1. Surface/Subsurface Volatiles
2. Reasonable terrain for traverse
3. Direct view to Earth for communication
4. Sunlight for duration of mission for power



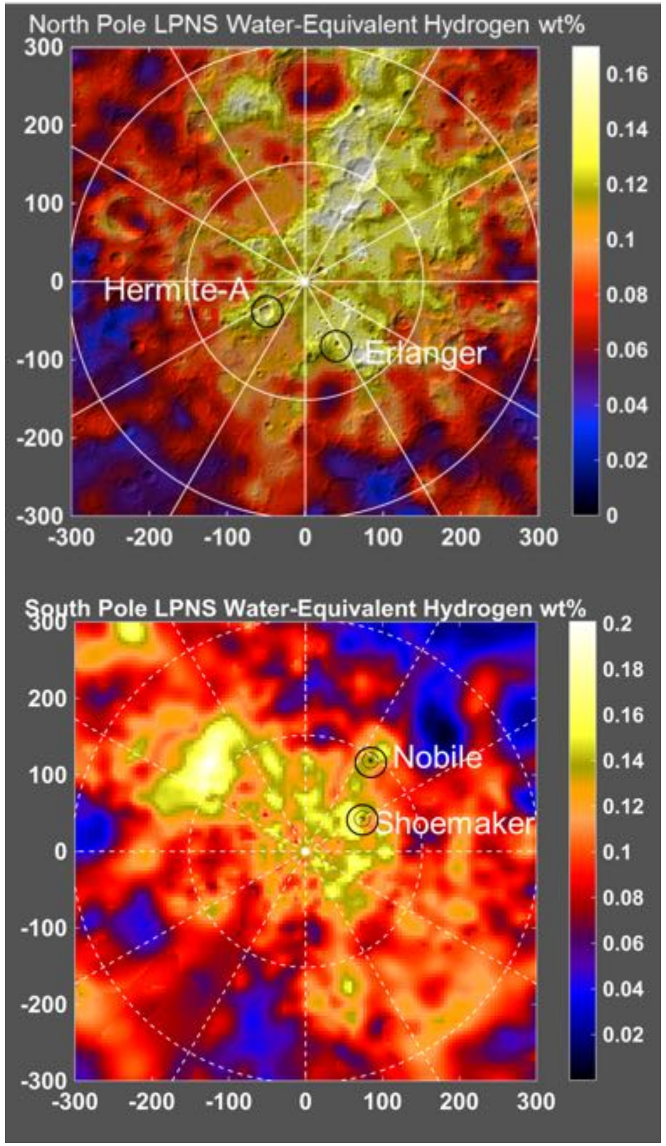
Site Selection - Process



Site Selection "Candidate" Test Locations

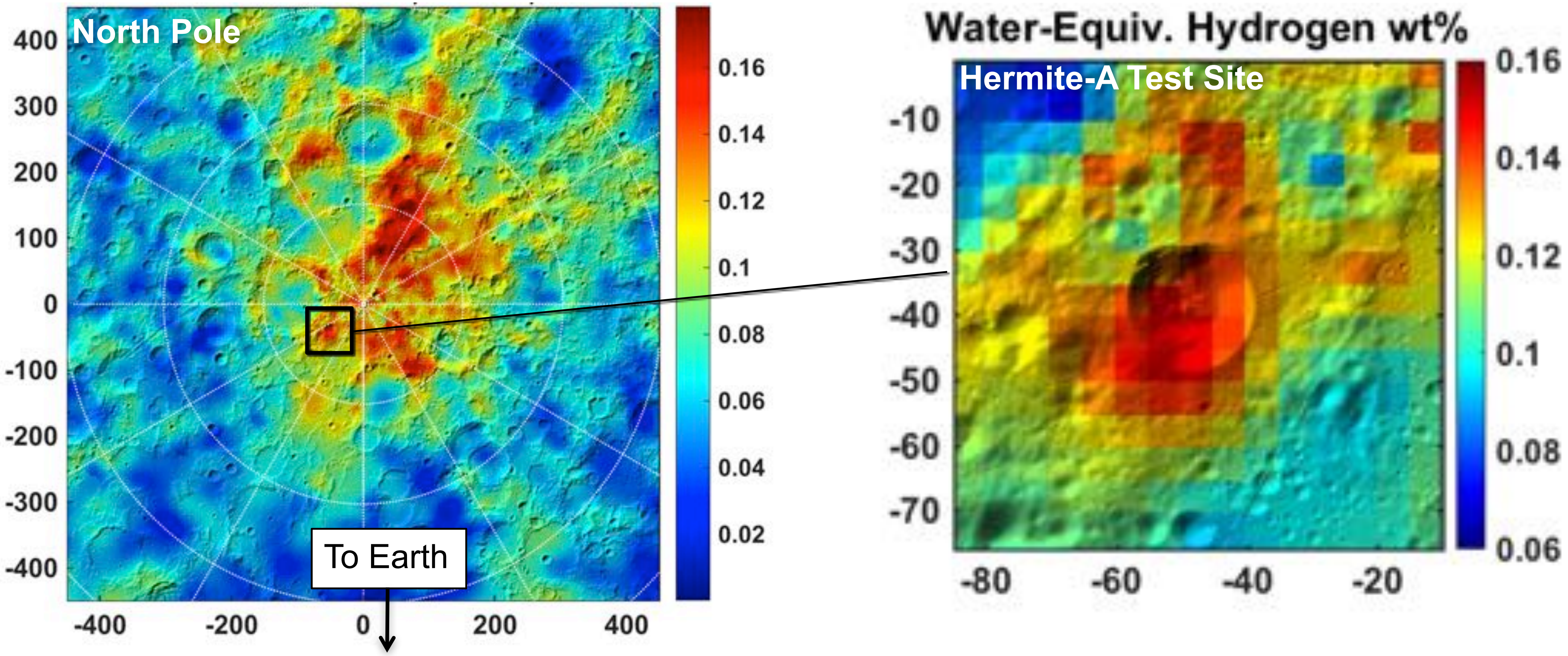
- The site selection process used 4 test locations with enhanced hydrogen.
- We have created multiple traverse plans in these test locations
- Traverse planning at these test sites provide data on needed data products, tools, an input to rover and operations development

		Site Center Coordiantes	
Pole	**Site Name**	**Lat.**	**Lon.**
SP	N. Nobile	-85.194S	35.436E
SP	N. Shoemaker	-87.185S	59.921E
NP	Erlanger	87.19N	29.119E
NP	Hermite-A	87.436N	-49.039E

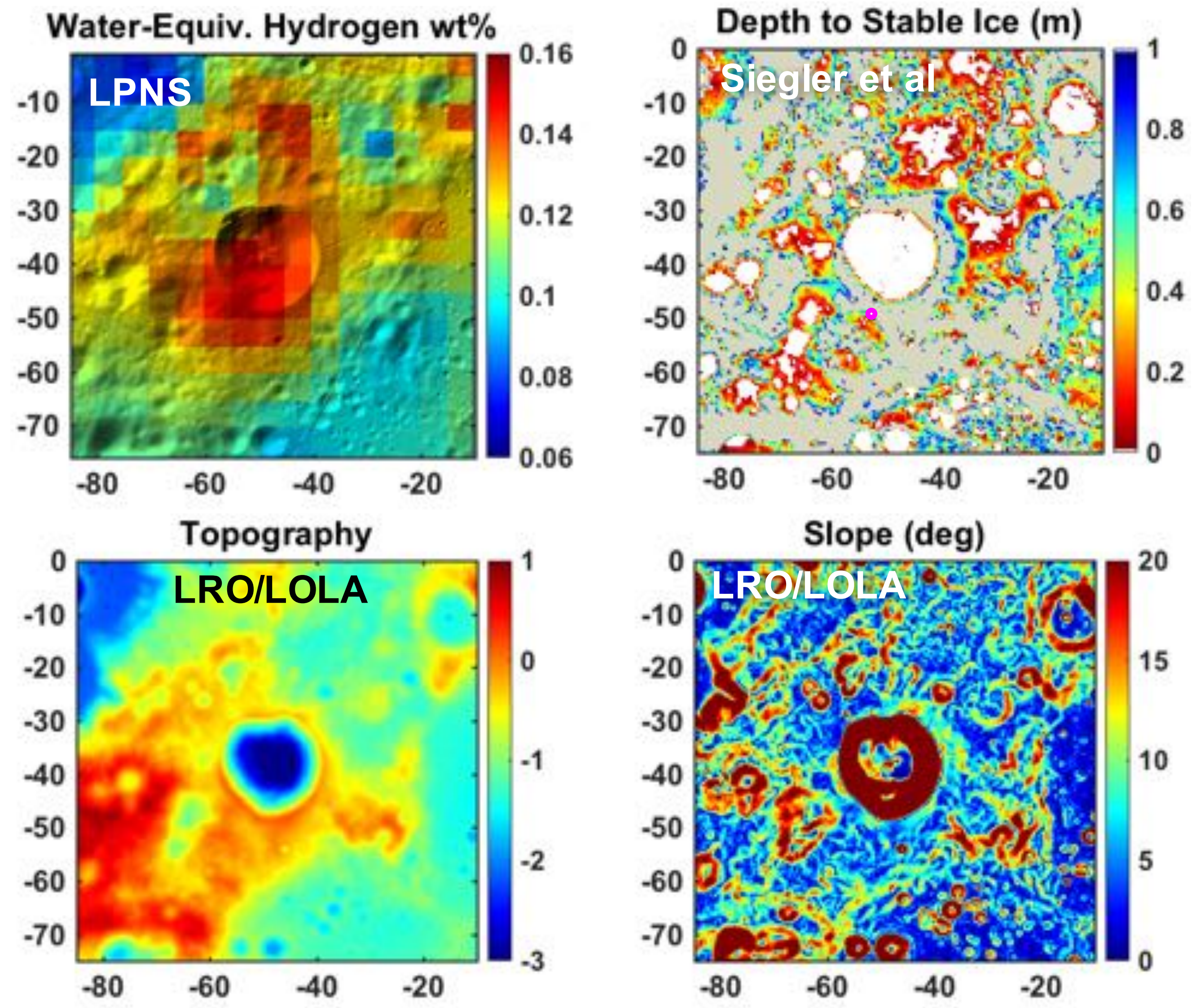


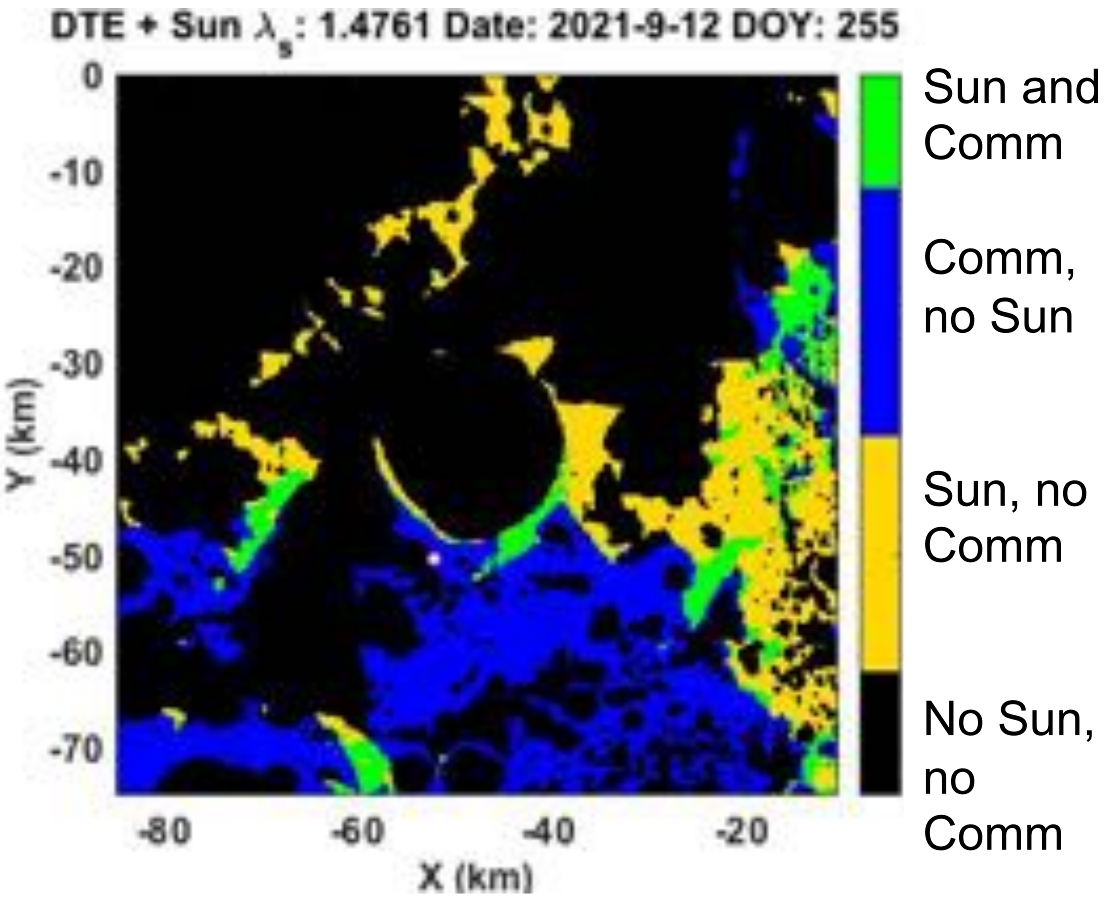
Surface/Subsurface Volatiles Regional Scale: Hydrogen Maps

- Hydrogen mapped by Lunar Prospector Neutron Spectrometer
- We don't have knowledge of volumetric hydrogen/water at scales smaller than several 10's km
  - We use "ice stability depth" modeling – described later.



Static and Dynamic Layers in Mission Planning: Hermite-A Example
Hydrogen, Topography, Slope, Ice Stability Depth vs Sun/Comm



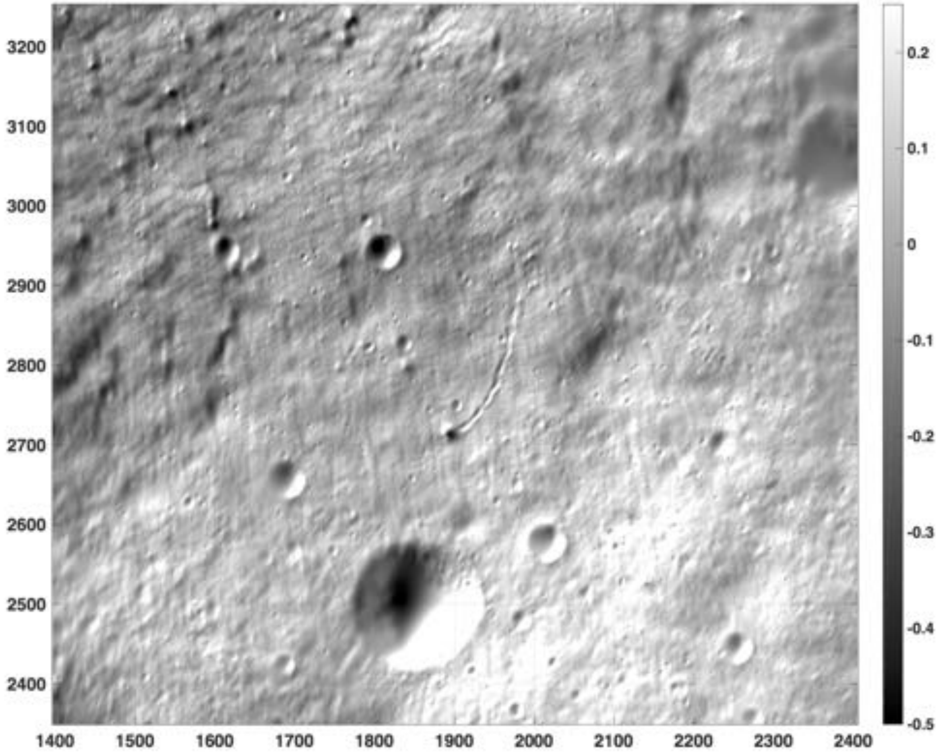


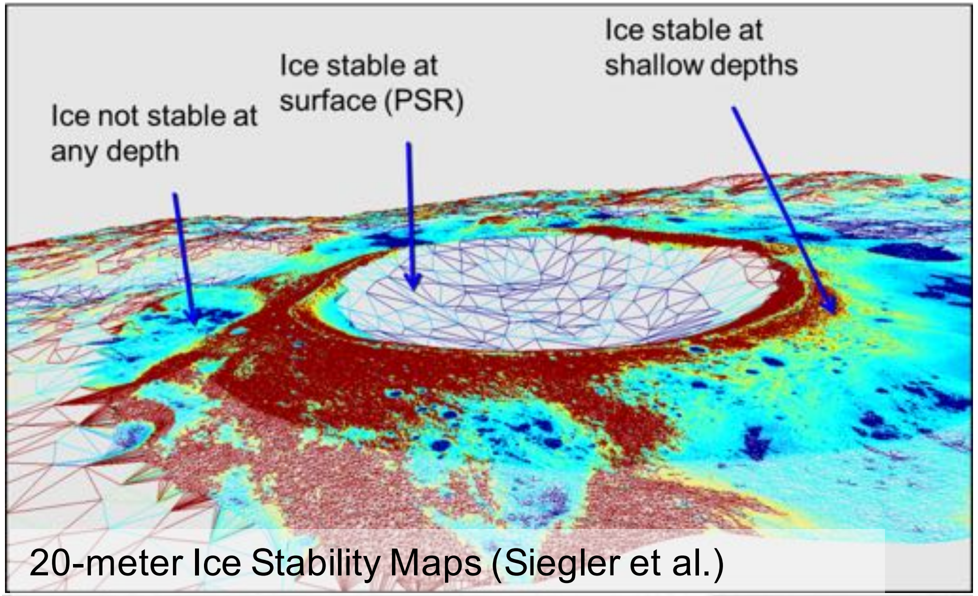
A Problem of Scales…

Rover design and traverse planing/operations desires (strongly!) data sets at or near the scale of the rover (~1m)

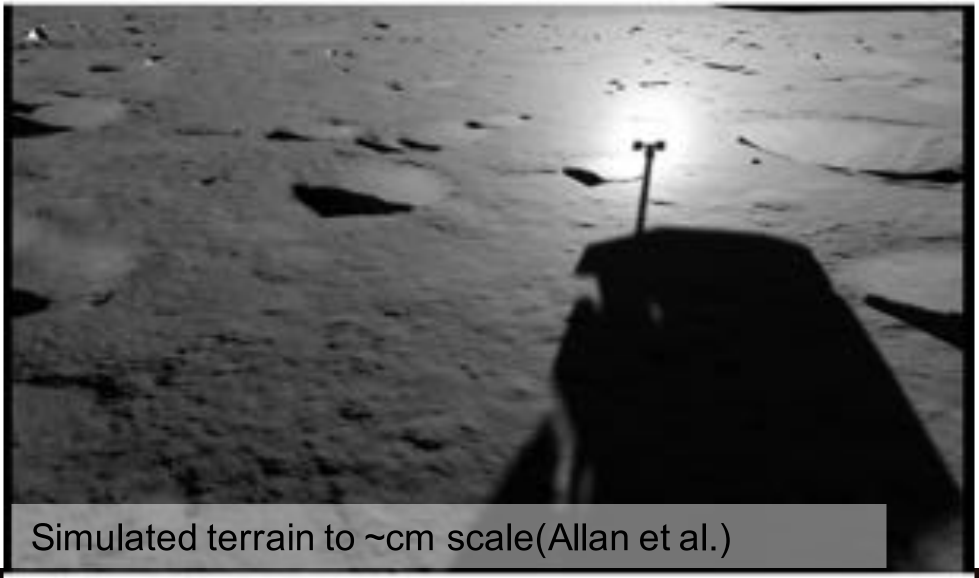
- Need to go from “standard” products 100s of meters to 1-10 meter posting

“Shape from Shadow” DEMs with 1m posting (Beyer et al.)



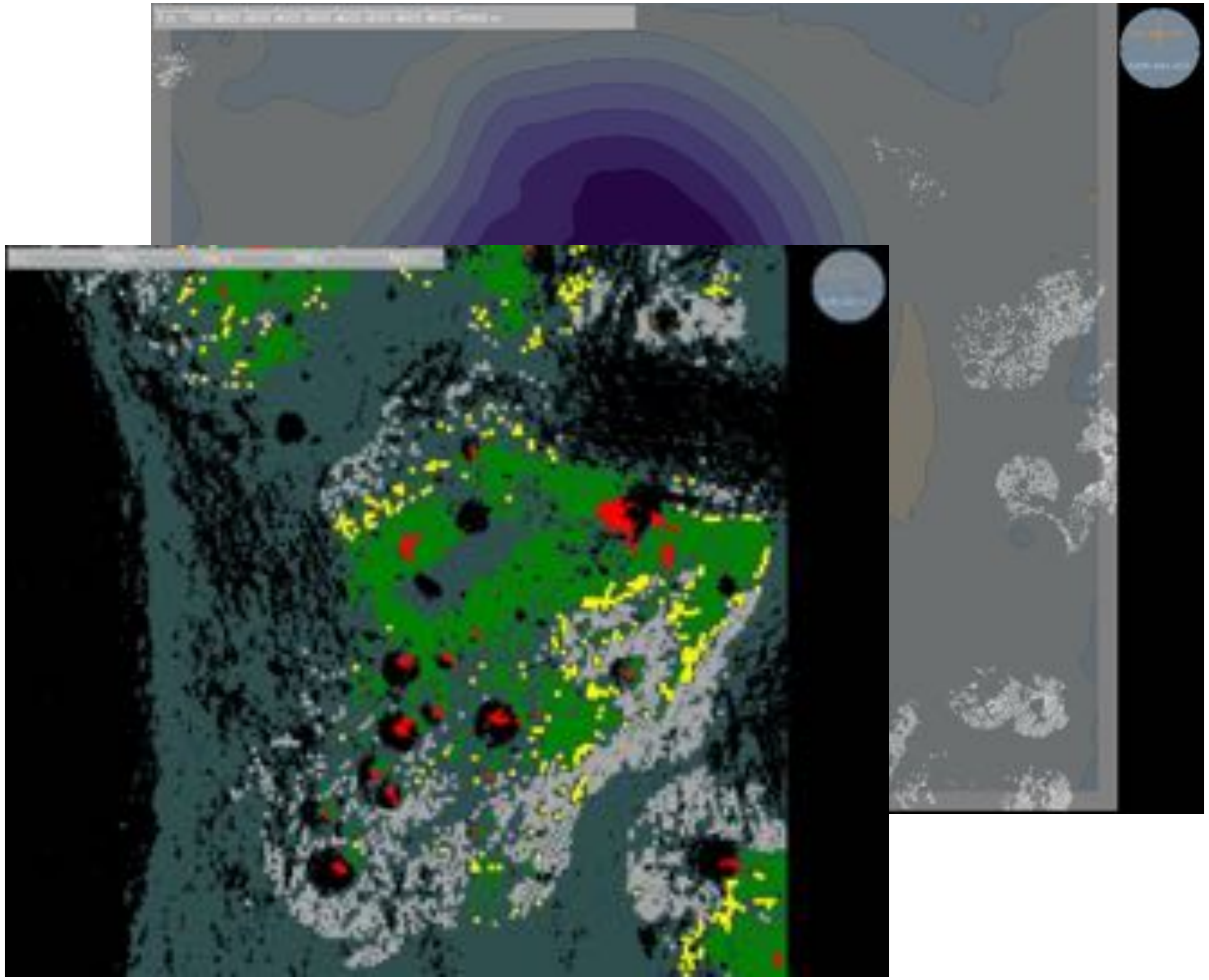


20-meter Ice Stability Maps (Siegler et al.)


Simulated terrain to ~cm scale(Allan et al.)

Automated Traverse Search Tool

- Approximately two-dozen traverses have been planned at four polar sites (two north and two south)
- Planning uses Traverse Planner Tool with waypoints placed by hand
- An automated traverse search tool has been developed to automatically find regions that meet basic requirements (not optimized)
- Has been applied to Hermite-A region, finding thousands of potential traverses (many very similar to each other)




Let's go.
Resource Prospector
NASA

Backup

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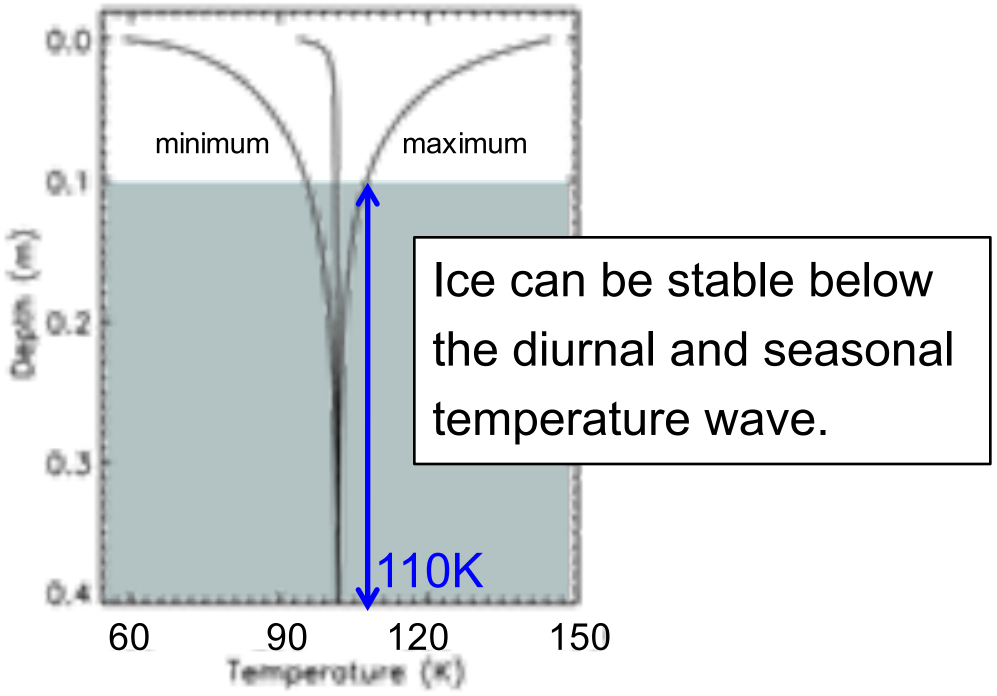
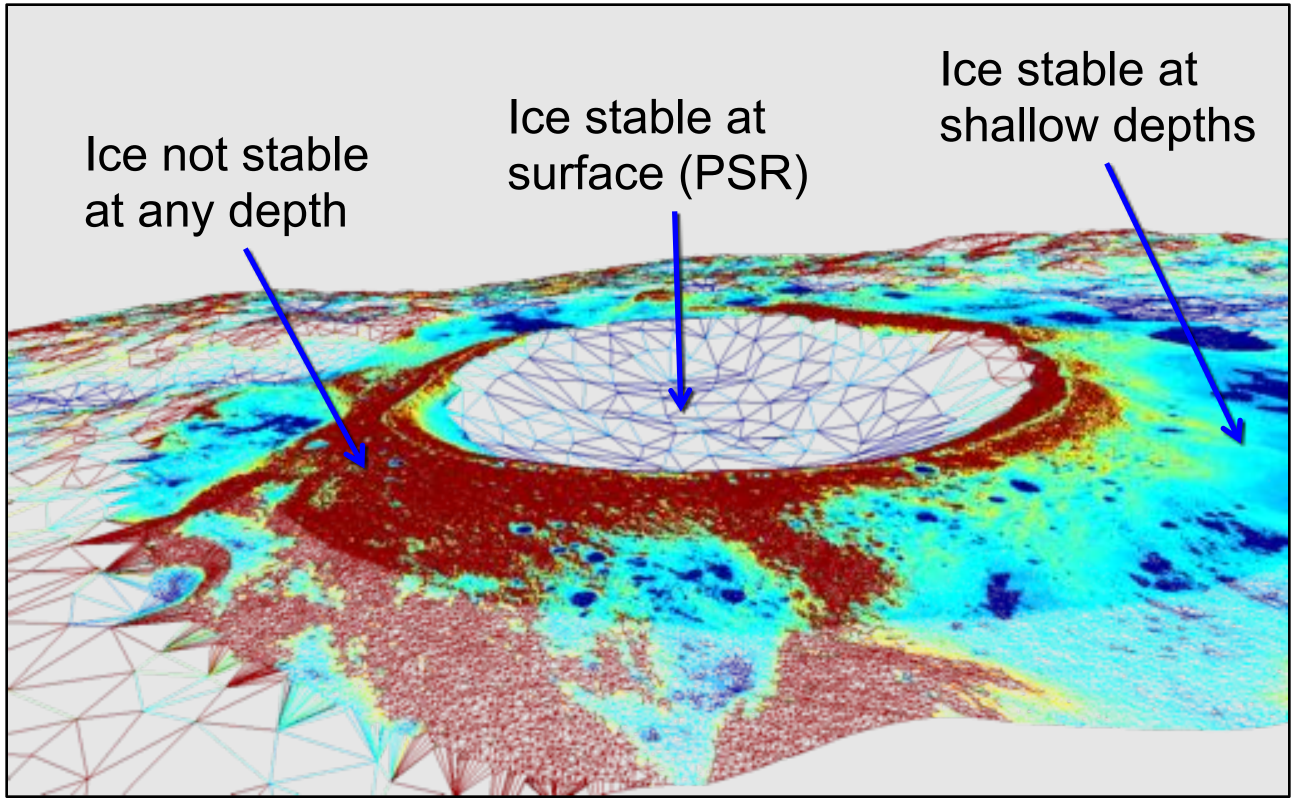
Target Scale Ice Stability Depth Modeling: Where *Could* Ice Be Stable?

- Problem: Hydrogen maps are 10's km resolution – too coarse for target-scale, detailed traverse planning.
- We know that *cryogenic* temperatures are necessary for long-term ice sequestration.
- *Matt Siegler* (PSI) and *Dave Paige* (UCLA) have developed high resolution ice stability depth modeling for RP.
  - Calculates equilibrium subsurface temperature profile for 1.2 million facets on a variable resolution mesh.
  - A run requires 10 days on 200 compute nodes at UCLA.

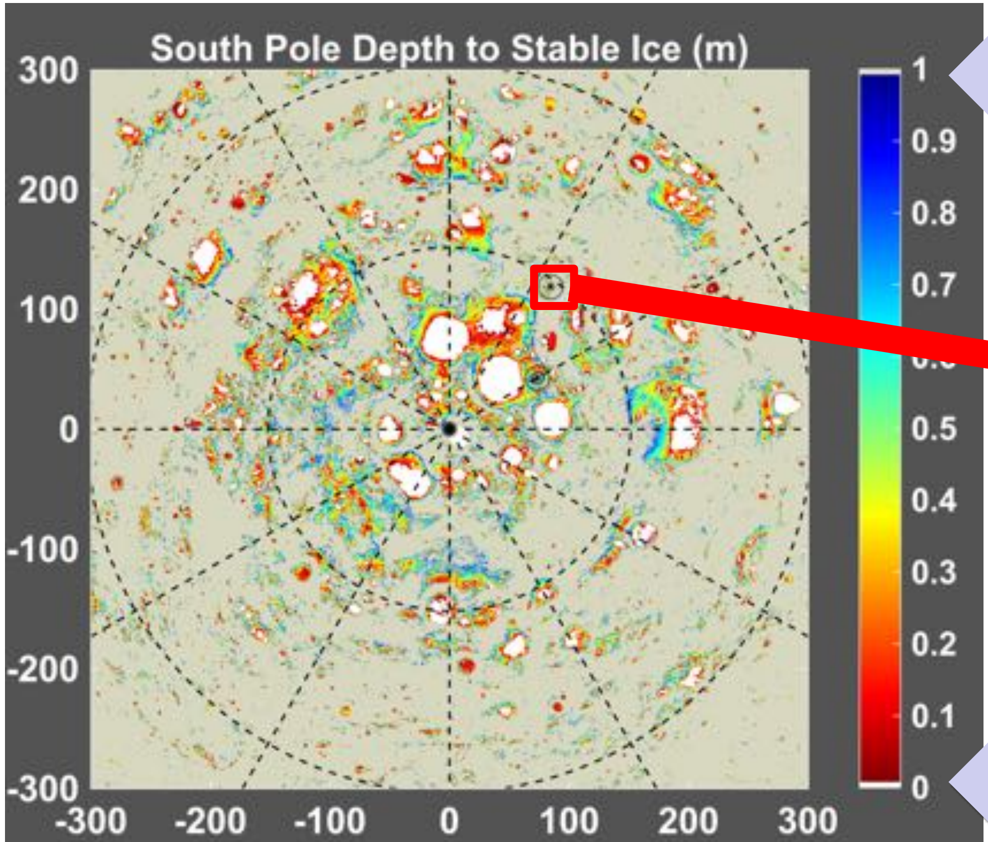


Adapted from Vasavada et al. 2012



Regional Scale Ice Stability Depth: Where *Could* Ice Be Stable?

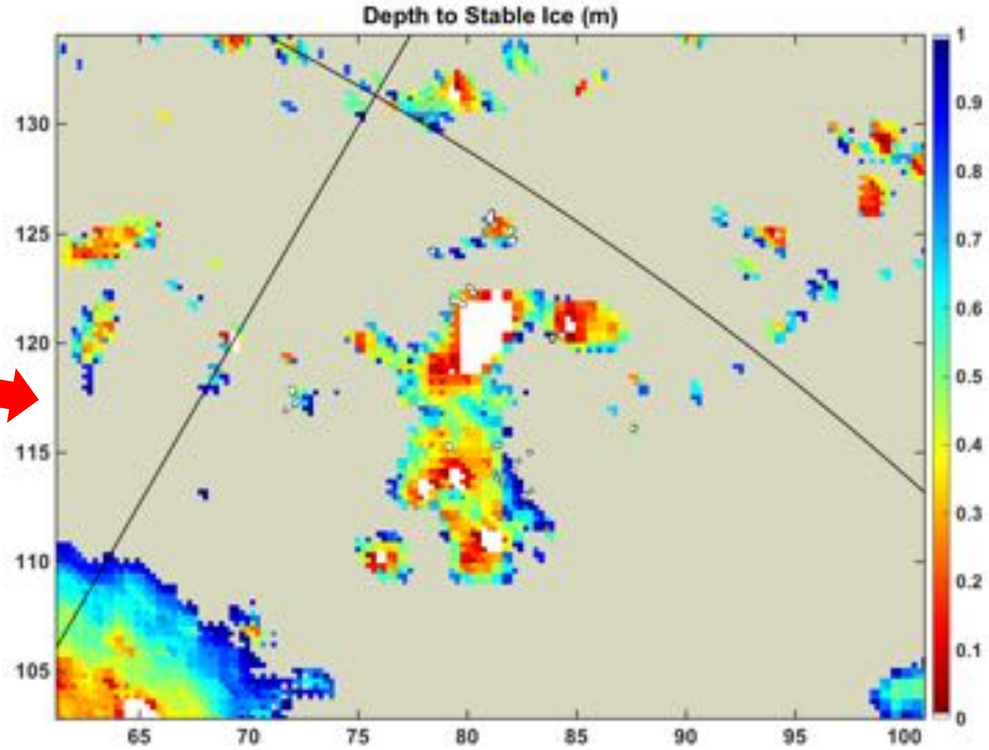
- “Fuzzy” hydrogen maps, so use ice stability depth model to determine where to land and explore.
- Below is the 240-m product for the entire south polar region.
- Inset shows the Nobile area, one of the test sites. Product has 240-m resolution.



Model data from Siegler et al., *Nature*, 2016

Not stable at depth <1 m

Stable at Surface



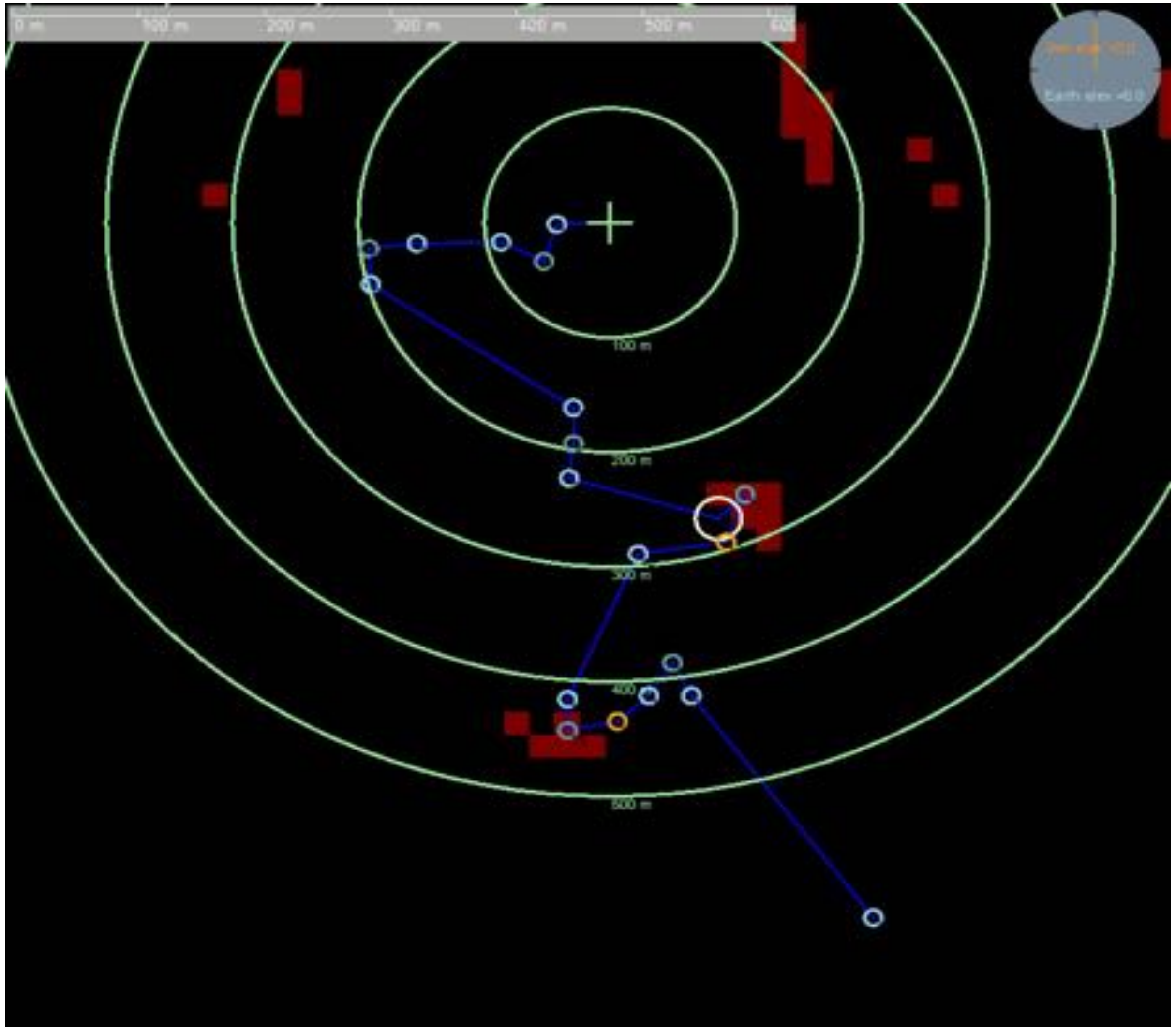
RP Traverse Example at Hermite-A

Achieves full mission success with margin

- Minimum measurement set in all 4 RTRs (includes 2 in PSR)

Other Planner Inputs / Constraints:

- **Activity Dictionary** (activities, durations, energy requirements, etc)
- **Waypoint Selection**
- **Power and Downlink Models** (array size, efficiency, rover power, etc)
- **Driving Speed** (speed made good)
- **Availability of sun and comm** (time and space dependent)
- **Trafficability** (identify keep out areas of hazardous slopes)
- Maps that combine other maps (AND-ing multiple layers)



Green = potential landing site, red=potential psr sample, grayscale=amt of sunlight, circles=drill sites